

Fe Content Dependence of Synthetic-Antiferromagnetic Coupling in Subnano-Crystalline FeCoB/Ru/FeCoB Films

Atsushi Hashimoto¹, Shin Saito¹, Dong Young Kim³, Hiroshi Takashima⁴, Tomonori Ueno⁴, and Migaku Takahashi^{1,2}

¹Department of Electronic Engineering, Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan

²New Industry Creation Hatchery Center, Tohoku University, Sendai 980-8579, Japan

³Research Center for Advanced Magnetic Materials, Chungnam National University, Daejeon 305-764, Korea

⁴Hitachi Metals Ltd., Yasugi 692-8601, Japan

Ru thickness (d_{Ru}) dependence of flopping field (H_f) was investigated in subnano-crystalline $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}/\text{Ru}/(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ films with various Fe content, x . The H_f with d_{Ru} showed oscillatory behavior with the period of 1.5 nm of d_{Ru} , which was independent of the Fe content. The first peak of H_f takes the maximum value at $x = 65$ at.%, and the second peak was degenerated with increasing the Fe content. These results are analyzed in terms of interlayer coupling effect including the bilinear (J_1) and biquadratic (J_2) coupling energy. As the d_{Ru} decreases, the J_1 oscillates and J_2 monotonously increases. Although the J_2 effect appeared at thinner d_{Ru} , i.e., $d_{\text{Ru}} < 0.7$ nm, the J_1 effect was rather stronger than the J_2 one. The magnitude of the first peak of J_1 was greatly enhanced with increasing Fe content, and took the maximum at $x = 65$ at.%. Therefore, a smooth interface was established in subnano-crystalline FeCoB, and the intrinsic strong J_1 was realized in FeCoB/Ru/FeCoB system even in ultrathin d_{Ru} of 0.3 nm.

Index Terms—Interlayer coupling, perpendicular recording medium, soft magnetic underlayer, subnano-crystalline FeCoB.

I. INTRODUCTION

II. EXPERIMENTAL PROCEDURE

IN HIGH recording density perpendicular recording media, a thick soft magnetic underlayer (SUL) is required for the magnetic flux closure. The thick SUL introduces spike noise and wide adjacent track erasure (WATE). The SUL with synthetic antiferromagnetic coupled (SAF) structure has the following two characteristics: 1) Néel walls are formed in the top and bottom soft magnetic (SM) layers in a pair [1] and 2) as interlayer coupling energy between two SM layers increases, susceptibility to the film normal takes low value even if the applying field angle is slightly tilted from the film normal. Since these properties are effective for suppression of both spike noise and WATE [2], the SUL with SAF structures have been widely investigated [3]–[5]. High saturation magnetization (M_s) materials are also required for thin SUL. Therefore, to improve SUL properties mentioned above, it is essential to enhance interlayer coupling induced in SUL with SAF structure using high M_s material. We already reported that the flopping field (H_f) and the saturation field (H_s) were greatly enhanced at the first peak of interlayer coupling phenomena in subnano-crystalline FeCoB/Ru/FeCoB film having high M_s value of 1520 emu/cm³ for SM layers even in $d_{\text{Ru}} = 0.3$ nm [6].

In this paper, we investigate the Fe content dependence of SAF coupling properties to clarify the mechanism of the enhanced H_f in $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}/\text{Ru}/(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ films with Fe content, x , in terms of interlayer coupling effect.

The $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ (30 nm)/Ru(d_{Ru})/ $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ (30 nm) films with Fe content, $x = 0, 30, 50, 65, 80$, and 100 at.% were fabricated by the dc magnetron sputtering method at room temperature. The sputtering target of $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ was prepared by the hot isostatic press method using atomized powders [7]. The $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ and Ru layers were deposited with deposition rate of 2.01–2.60 nm/s and 0.15 nm/s under the Ar pressure of 0.6 Pa, respectively. The composition of the sputtered FeCoB films was confirmed by the inductively coupled plasma method. The measured Fe composition was about 2 at.% less than that of the target, and the boron content was not changed. Magnetic properties of the samples were evaluated using a vibrating sample magnetometer.

III. RESULTS AND DISCUSSION

A. Stacking Structure of FeCoB/Ru/FeCoB Film

Stacking structure is confirmed for a typical sample which shows large H_f and H_s . Fig. 1 shows the cross-sectional TEM image for $(\text{Fe}_{65}\text{Co}_{35})_{88}\text{B}_{12}$ (30 nm)/Ru (0.3 nm)/ $(\text{Fe}_{65}\text{Co}_{35})_{88}\text{B}_{12}$ (30 nm) film. The interfaces between the FeCoB/Ru layers and the film surface are quite smooth. The small swell with long distance period observed at the interface and the surface was found to correspond to the surface roughness of substrate. The enhanced smoothness at the interface between FeCoB and Ru or Ru and FeCoB was caused by the subnano-crystalline structure of FeCoB [6]. Therefore, in this work, interlayer ferromagnetic coupling (Néel coupling) originated from interlayer roughness can be suppressed because of the flat interface.

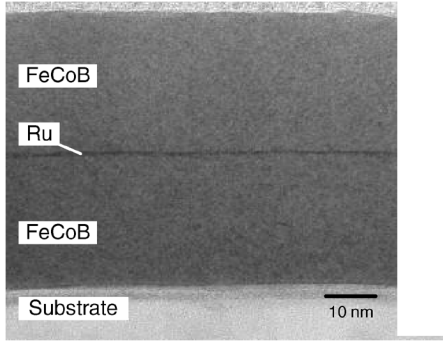


Fig. 1. Cross-sectional TEM image for $(\text{Fe}_{65}\text{Co}_{35})_{88}\text{B}_{12}(30 \text{ nm})/\text{Ru}(0.3 \text{ nm})/(\text{Fe}_{65}\text{Co}_{35})_{88}\text{B}_{12}(30 \text{ nm})$ film.

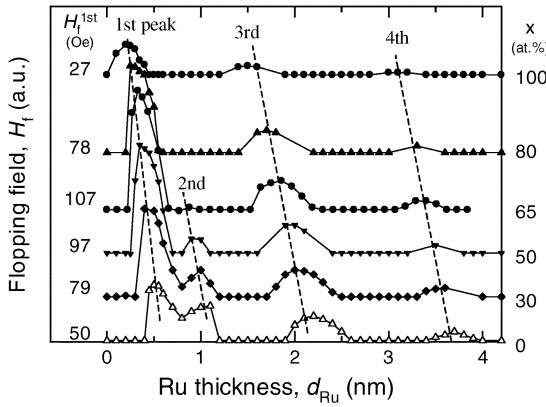


Fig. 2. Ru thickness dependence of H_f for $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}(30 \text{ nm})/\text{Ru}(d_{\text{Ru}} \text{ nm})/(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}(30 \text{ nm})$ films with various Fe content, x . H_f values at the first peak are shown in the figure.

B. Oscillatory Behavior of Flopping and Saturation Field

Fig. 2 shows the d_{Ru} dependence of the H_f for $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}/\text{Ru}/(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ films. In the case of $x = 0$, with decreasing d_{Ru} , H_f shows oscillatory behavior with taking the local maximum at $d_{\text{Ru}} = 3.4, 2.2, 1.0$, and 0.5 nm . Each peak is indicated as the fourth, third, second, and first peak with d_{Ru} . The largest H_f value is observed at the first peak. As the Fe content increases, the H_f value at the first peak increases and takes the maximum at $x = 65 \text{ at.}\%$, whereas H_f at the second peak decreases and hardly was observed over $x = 65 \text{ at.}\%$.

Fig. 3 shows the d_{Ru} dependence of H_s for $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}/\text{Ru}/(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ films. Here, the H_s values are determined at the magnetic field representing 95 % of M_s in the M - H loop measured at hard magnetized axis. H_s also shows oscillatory behavior with d_{Ru} . H_s of the first peak is also strongly enhanced as Fe content increases from 0 to 65 at. %.

C. Evaluation of Interlayer Coupling Energy

The mechanism of enhancement of the H_f at the first peak in FeCoB/Ru/FeCoB films is quantitatively evaluated in terms of interlayer coupling effect including the bilinear and biquadratic coupling energy. The total magnetic energy per unit area (E_T)

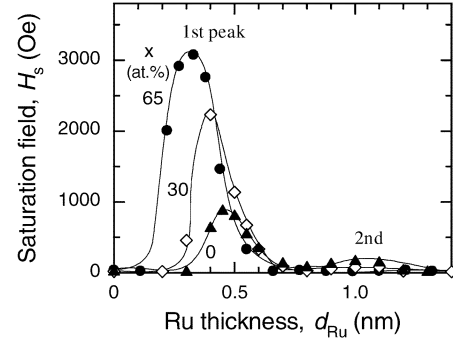


Fig. 3. Ru thickness dependence of H_s for $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}/\text{Ru}/(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ films with $x = 0, 30$, and 65 .

including bilinear coupling energy, $J_1 \cos(\phi_1 - \phi_2)$, and bi-quadratic coupling energy, $J_2 \cos^2(\phi_1 - \phi_2)$, in SAF structure is expressed as follows [8]:

$$E_T = K_u d_{\text{SM}} (\sin^2 \phi_1 + \sin^2 \phi_2) + J_1 \cos(\phi_1 - \phi_2) + J_2 \cos^2(\phi_1 - \phi_2) - M_s H d_{\text{SM}} (\cos \phi_1 + \cos \phi_2). \quad (1)$$

The d_{SM} and K_u denote the thickness and uniaxial magnetic anisotropy energy of SM layer, respectively. ϕ_1 and ϕ_2 denote the angles between the easy magnetized axis and the magnetic moment of top and bottom SM layers, respectively. Note that in this equation, domain structure and dispersion of magnetic anisotropy are not considered. The net magnetization of the two SM layers is calculated by the equilibrium angle of ϕ_1 and ϕ_2 , which were determined from the minimum energy condition of (1). Then M - H loop is derived using the following equation:

$$M = M_s (\cos \phi_1 + \cos \phi_2). \quad (2)$$

To explain the enhancement of H_f at the first peak in $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}/\text{Ru}/(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ film, the values of J_1 and J_2 are evaluated from the best fitting of measured M - H loop by using (1) [5]. In fitting, correspondence of M - H loops until a half of rotation reversal region was regarded as important (see the inset figure in Fig. 4). The values of K_u and M_s were experimentally obtained and are summarized in Table I.

Fig. 4(a) and (b) shows evaluated J_1 and J_2 against d_{Ru} , respectively. As d_{Ru} decreases, J_1 oscillates and magnitude of the local maximum increases, while J_2 monotonously increases at less than $d_{\text{Ru}} = 0.7 \text{ nm}$.

Now, the origin of the enhancement of H_f is discussed focusing on J_1 and J_2 . At the first peak of H_f , concerning that J_1 and J_2 are one or two figures larger than $K_u d_{\text{SM}}$ and that J_1 is larger than $2 J_2$ [see Table I, Fig. 4(a) and (b)], H_f can be expressed as follows:

$$H_f = (2/M_s d_{\text{SM}}) \sqrt{K_u d_{\text{SM}} (J_1 - 2J_2 - K_u d_{\text{SM}})} \approx (2/M_s d_{\text{SM}}) \sqrt{K_u d_{\text{SM}} (J_1 - 2J_2)}. \quad (3)$$

According to (3), H_f has linear relationship with $\sqrt{J_1 - 2J_2}$. As shown in Fig. 4(a) and (b), in the present films, $J_1 - 2J_2$ takes the maximum at the same d_{Ru} as J_1 . Therefore, the enhancement of H_f of the first peak is originated from the extreme enhancement of J_1 .

Finally, Fe content dependence of interlayer coupling for stacked films is discussed. Fig. 5 shows variation of

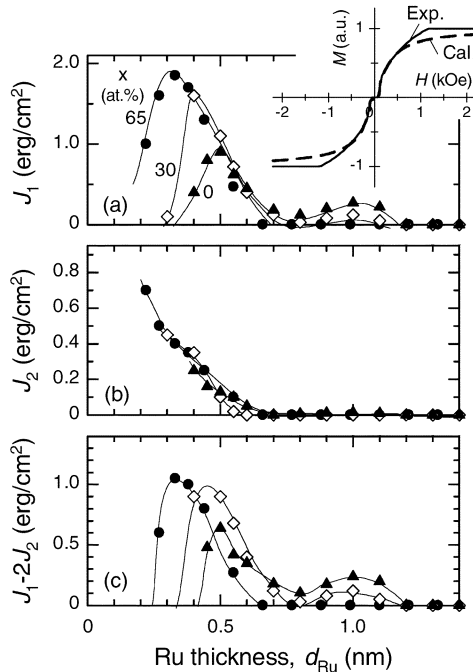


Fig. 4. The variation of (a) J_1 , (b) J_2 , and (c) $J_1 - 2J_2$ as a function of Ru thickness for $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}/\text{Ru}/(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ films with $x = 0, 30$ and 65 . The inset shows typical result of fitting for M - H loop. Solid and broken lines in the inset correspond to experimental and calculated results, respectively, for the sample with $x = 65$.

TABLE I
MAGNETIC PROPERTIES FOR $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ SPUTTERED FILMS
WITH VARIOUS Fe CONTENT, x

x	at. %	0	30	50	65	80	100
M_s	emu/cm ³	1130	1260	1580	1520	1680	1440
K_u	10 ³ erg/cm ³	5.0	6.0	10	14	9	2
$K_u d_{\text{SM}}$	10 ² erg/cm ²	1.5	2.1	3.0	4.2	2.7	0.6

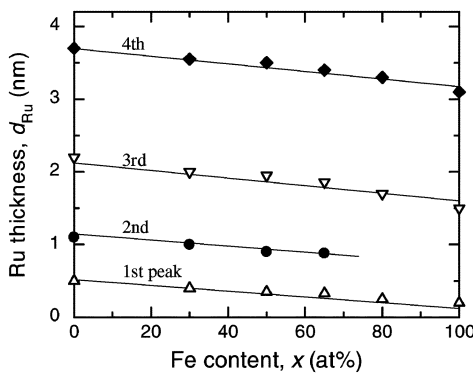


Fig. 5. The variation of peak position depending on Fe content, x , for $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}/\text{Ru}/(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ films.

d_{Ru} at the first, second, third, and fourth peaks of H_f for $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}/\text{Ru}/(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ films as a function of Fe content. As the Fe content increases, every peak thicknesses shift toward small thickness side. Focusing on the peak-to-peak thickness, except for the second peak, thicknesses of the first-to-third and the third-to-fourth peaks take the same value of 1.5 nm. These results indicate that oscillatory behavior of the first, third, and fourth peaks originate from an RKKY-type indirect coupling effect [9], and that the oscillation

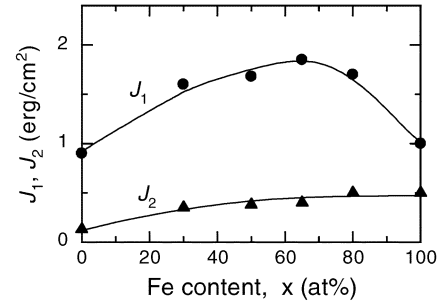


Fig. 6. The maximum values of J_1 and J_2 as a function of Fe content, x , for $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}/\text{Ru}/(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ films.

period and phase are determined by Ru and the compositional ratio of CoFe, respectively.

Fig. 6 shows J_1 and J_2 of the first peak for $(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}/\text{Ru}/(\text{Co}_{100-x}\text{Fe}_x)_{88}\text{B}_{12}$ films against Fe content. As Fe content increases from 0 to 65 at.%, J_1 greatly increases from 0.9 to 1.9 erg/cm², while J_2 increases slightly from 0.1 to 0.4 erg/cm². From these results, it is revealed that FeCoB/Ru/FeCoB sputtered films can realize smooth interface and induction of strong J_1 due to subnano-crystalline FeCoB even in ultrathin d_{Ru} .

Thus, FeCoB/Ru/FeCoB film with high Fe content is promising candidate for SUL in perpendicular recording medium because of high M_s , smooth interface, and strong J_1 at ultrathin d_{Ru} .

ACKNOWLEDGMENT

The authors would like to thank Mr. Goto from Ohara Inc. for contributing the substrates used in this experiment.

REFERENCES

- [1] S. Iida, S. Iwasaki, Y. Iwama, H. Kobayashi, Y. Sakurai, T. Nagashima, and S. Watanabe, *Engineering of Magnetic Thin Films (in Japanese)*, Maruzen, Japan, 1977, p. 231.
- [2] A. Hashimoto, S. Saito, and M. Takahashi, "A soft magnetic underlayer with negative uniaxial magnetocrystalline anisotropy for suppression of spike noise and wide adjacent track erasure in perpendicular recording media," *J. Appl. Phys.*, vol. 99, no. 08Q907, 2006.
- [3] S. Saito, K. Hirai, A. Hashimoto, M. Tsunoda, and M. Takahashi, "Material problems in soft-magnetic underlayers with high stray-field stability using interlayer magnetic coupling," *J. Magn. Soc. Jpn.*, vol. 27, p. 224, 2003.
- [4] B. R. Acharya, J. N. Zhou, M. Zheng, G. Choe, E. N. Abarra, and K. E. Johnson, "Anti-parallel coupled soft under layers for high-density perpendicular recording," *IEEE Trans. Magn.*, vol. 40, no. 4, pp. 2383–2385, Jul. 2004.
- [5] S. C. Byeon, A. Misra, and W. D. Doyle, "Synthetic antiferromagnetic soft underlayers for perpendicular recording media," *IEEE Trans. Magn.*, vol. 40, no. 4, pp. 2386–2388, Jul. 2004.
- [6] A. Hashimoto, S. Saito, K. Omori, H. Takashima, T. Ueno, and M. Takahashi, "Marked enhancement of synthetic-antiferromagnetic coupling in subnano-crystalline FeCoB/Ru/FeCoB sputtered films," *Appl. Phys. Lett.*, 2006, submitted for publication.
- [7] H. Ueno, T. Ueno, and S. Yokoyama, "Development of Fe-Co-B target material for perpendicular magnetic recording," in *Dig. Annu. Conf. Magn. Jpn. 2004*, vol. 21pB-4.
- [8] J. F. Bobo, H. Kikuchi, O. Redon, E. Snoeck, M. Piecuch, and R. L. White, "Pinholes in antiferromagnetically coupled multilayers: Effect on hysteresis loops and relation to biquadratic exchange," *Phys. Rev. B*, vol. 60, p. 4131, 1999.
- [9] S. S. P. Parkin, "Systematic variation of the strength and oscillation period of indirect magnetic exchange coupling through the 3d, 4d, and 5d transition metals," *Phys. Rev. Lett.*, vol. 67, p. 3598, 1991.

Manuscript received March 13, 2006; revised June 12, 2006 (e-mail: a-hashi@ecei.tohoku.ac.jp).